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# AIR DISTRIBUTION IN A FURNISHED ROOM VENTILATED BY MIXING VENTILATION

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## ABSTRACT

Using isothermal full-scale experiments and two-dimensional isothermal CFD simulations it is investigated how normal office furniture influences the air movements in a room with mixing ventilation. Three different set-ups are made in the experiments and different sizes and locations of the furniture volume are simulated. The simulations are made in three different lengths of the room.

The investigations are concerning influence of the furniture on the wall jet under the ceiling and the maximum velocity in the occupied zone.

Two methods to determine the maximum velocity in the occupied zone are developed. The first method uses the total length of the furniture (volume) as a parameter and the second uses the downstream distance from the inlet to the beginning of the furniture (volume) as a parameter.

It can, on basis of the investigations made in this paper, be concluded that normal office furniture does not influence the air movements in the upper part of the room but it reduces the maximum velocity in the occupied zone compared to an empty room. This reduction is dependent of the length and location of the furniture.

## KEYWORDS

Mixing Ventilation, CFD, Office Furniture, Occupied Zone, Wall Jet, Maximum Velocity.

## INTRODUCTION

The air distribution in a ventilated room is determined for the feeling of comfort. One of the vital factors to the thermal comfort is the air velocity in the occupied zone. Too high velocities cause draught and thereby discomfort. Therefore a number of methods are used to design ventilation systems so that discomfort is avoided. These methods are developed on basis of experiments and simulations carried out in empty rooms although, furniture and people are present in practice in the room. Figure 1 indicates a large difference between an empty and a furnished room. In this paper a furnished room is investigated to see how much the air movements in the room changes compared to an empty room. The focus is on the inlet jet under the ceiling and the maximum velocity in the occupied zone.

The investigations are based on isothermal, full-scale experiments in a room with mixing ventilation as well as two-dimensional, isothermal Computational Fluid Dynamics (CFD) simulations. Normal office furniture is used in the test room.

It has earlier been shown that the wall jet under the ceiling is slightly influenced by very large obstacles in the occupied zone (Nielson et al. 1996), and this effect is also studied in this paper.

The velocity level and the maximum velocity in the occupied zone is important to the thermal comfort and Nielsen et al. (1996) found that the velocity level and thereby also the maximum velocity is reduced by large obstacles in the occupied zone. This paper gives a quantification of the influence from normal office furniture on the maximum velocity in the occupied zone.

## EXPERIMENTS AND SIMULATIONS

Isothermal, full-scale experiments with normal office furniture are carried out in a room with the size (L×W×H) 5.4×3.6×2.5 m. The inlet covers the total width of the room and it is located 0.25 m from the one end wall, see figure 3. The height of the slot is 0.01 m and it is located 0.023 m under the ceiling. The exhaust is placed on the same end wall as the inlet close to the floor. The inlet velocity is 3.47 m/s in all experiments and simulations described in this paper.

In the experiments normal office furniture is placed in the half of the room opposite to the inlet. Three different set-ups are made and they are all symmetrical around the centre-line of the room, see figure 2. The office furniture consists of: two desks, two computer tables with computers and two cylinders (H×D) 1.0×0.4 m representing two sitting persons. The side of the computer tables closest to the inlet is parallel to the middle of the room. In the three set-ups the location of the desks is changed, see figure 2.

The three office situations have also been simulated with CFD. In the two-dimensional, isothermal simulations the equations for continuity and x- and y-momentum (Navier-Stokes equation) together with the k-ϵ model for turbulence have been used. Instead of specifying a detailed geometry of the furniture a volume resistance generating a pressure drop is used. In all the simulations described in this paper the volume resistance covers the entire width of the room. The pressure drop in the volume resistance is determined by (Flomerics, 1994):

$$\frac{\partial p}{\partial x} = \frac{f}{2}\rho u^2 \tag{1}$$

where $\partial p/\partial x$ : Pressure drop per m [Pa/m].
$f$ : Loss coefficient.
$\rho$ : Air density; 1.19 kg/m³.
$u$ : Velocity [m/s].

To determine the value of the loss coefficient, f, the velocity profile 2.0 m from the inlet is compared with the measured profile. This position is chosen because at this location the jet at the ceiling is fully developed and the location is outside the furnished area. Thereby only the average effect of the furniture on the air movements in the room is taken into account.

To determine the loss coefficient, f, two volume resistances are used: one having the length of the desk and one having the length of the computer tables. Due to the different location of the desks in the experiments, two simulations are necessary, see figure 3. In set-up 1 the person is included in the volume resistance closest to the end wall. The loss coefficient, f, giving the best agreement with the measurements is found to be approximately 0.5, see figure 4.

Further two-dimensional, isothermal simulations have been made with volume resistances (f=0.5) representing normal office furniture in order to investigate the importance of the location, the length and the height of the furniture volume. In all the simulations the volume resistance is located in the half of the room opposite to the inlet but the distance to the wall opposite to the inlet is varying. There is simulated with lengths of the furniture volume between 0.25 and 2.70 m and the heights vary between 0.5 and 2.0 m equal to 0.2H-0.8H. The importance of the number of volumes have also been investigated.

Finally a number of similar simulations have been made with two alternative lengths of the room: 3.75 and 7.50 m equal to 1.5H and 3.0H respectively. In these simulations the distance from the end wall opposite the inlet to the volume resistance is the same as in the 5.4 m long room and the size of the volume resistance is maintained, see figure 5.

## RESULTS AND DISCUSSION

The jet under the ceiling is investigated to see how much normal office furniture influences the air movements in the upper part of the room. The maximum velocity in the occupied zone is also studied. Two methods to predict the maximum velocity in the occupied zone are proposed. In the first the total length of the furniture (volume) is used as a parameter and in the second the downstream distance the jet travels from the inlet to the beginning of the furniture (volume) is used as a parameter. It is important to be aware of that the methods proposed in this paper are only valid when the furniture is located in the half of the room opposite to the inlet.

### Jet under the Ceiling

A study of the jet under the ceiling is important to determine whether the theory of jets used as flow elements in design procedures (throw) is fully valid in furnished rooms. The velocity decay at the ceiling is examined to find the influence of normal office furniture on the wall jet. The velocity decay is determined by (Rajartnam, 1976):

$$\frac{u_{\max}}{u_0} = K_p \sqrt{\frac{h}{x}} \tag{2}$$

where $u_{max}$ : Maximum velocity of the jet at the distance x from the supply opening [m/s].
$u_0$ : Inlet velocity [m/s].
$K_p$ : Individual constant of the diffuser.
$h$ : Height of the supply opening [m].
$x$ : Distance from the supply opening [m].

When the equation above is used in the design process, the individual constant of the diffuser, $K_p$, is known and thereby the velocity decay can be found. Here the equation is used to find $K_p$ from a known velocity decay. This means that if the furniture does not influence the wall jet, $K_p$ will be constant and equal to the one found in the empty room.

In all three lengths of the room it is found that the value of $K_p$ is uninfluenced by the furniture in the room and the location and size of the furniture does not affect the jet either. In the three lengths of the room: 5.40, 3.75 and 7.50 m, $K_p$ is found to 3.2, 3.2 and 2.9 respectively. This difference in $K_p$ is caused by the influence of the length of the room and not by the furniture. It can therefore be concluded that normal office furniture located in the half of the room opposite to the inlet has no effect on the jet under the ceiling and thereby the flow element theory (throw) developed in empty rooms is also valid in normally furnished rooms.

**Maximum Velocity in the Occupied Zone and the Total Length of the Furniture Volume**

The maximum velocity in the occupied zone of a furnished room can be determined when the total length of the furniture volume is known. In this paper the definition of total length of the furniture volume is the summation of the lengths in the main flow direction where furniture is present. For example in set-up 1 the total length of the furniture is the summation of the width of the desk, the diameter of the person/cylinder and the width of the computer table, and in set-up 2 and 3 the total length of the furniture is the summation of the length of the desk and the width of the computer table.

Figure 6 shows the connection between the maximum velocity in the occupied zone of a furnished room and the total length of the furniture volume in the room. The maximum velocity in the furnished room, $u_{rm}$, is non-dimensionalized with the maximum velocity in the occupied zone of the empty room, $u_{rm,0}$. The measured maximum velocity in the occupied zone in the empty full-scale room is 0.52 m/s and the calculated maximum velocities are 0.49, 0.38 and 0.29 m/s in the 3.75, 5.40 and 7.50 m long room respectively. Results from the experiments and the simulations in all three lengths of the room are plotted in the figure. Furthermore the regression line from the simulations is drawn in the figure. The equation for the regression line is:

$$\frac{u_{rm}}{u_{rm,0}} = 1 - C \cdot L_{fur} \qquad (3)$$

where $u_{rm}$ : Maximum velocity in the occupied zone in the furnished room [m/s].
$u_{rm,0}$ : Maximum velocity in the occupied zone in the empty room [m/s].
$C$ : A constant of 0.088 [$m^{-1}$].
$L_{fur}$ : Total length of the furniture volume [m].

The maximum velocity in the occupied zone of the empty room, $u_{rm,0}$, can be found either by experiments, simulations or by the use of design methods (Nielson, 1991) for determination of the maximum velocity in the occupied zone.

In figure 6 a difference in the maximum velocity appears between the experiments and the simulations. This is caused by the air having to flow around the physical furniture in the experiments whereas the volume resistance used in the simulations makes an uniform disturbance to the flow and because f is chosen on basis of the velocity level outside the furniture area. It can also be seen in figure 6 that the maximum velocity in the experimental set-up 2 is lower than the maximum velocities in set-up 1 and 3. The reason is the location of the desks in the middle of the room. They thereby influence the measurements which are made at the centre-line of the room.

Figure 6 shows that the maximum velocities in the occupied zone in the furnished room are lower than the maximum velocity found in the empty room. Thereby the standard method used to design a draught free air distribution system is a "safe" method because it is expected that the velocity in the furnished room often is lower than the design value obtained from an empty room.

The figure also shows that the results found in rooms of different length can fulfill the scale of reduction in maximum velocity in the occupied zone. The total length of the furniture volume influences the maximum velocity in the occupied zone and it is seen both from figure 6 and equation (3) that the maximum velocity in the occupied zone decreases with increasing furniture volume.

**Maximum Velocity in the Occupied Zone and the Distance from the Inlet to the Furniture Volume**

The determination of the maximum velocity in the occupied zone of a furnished room can also be based on the location of the furniture volume. It is necessary to know the size of the room and the location of the inlet. The maximum velocity in the occupied zone is determined on basis of the downstream distance the jet travels from the inlet to the beginning of the furniture, see figure 7. Where more than one group of furniture is present in the room the distance to the upwind group is used.

In figure 8 the connection between the maximum velocity in the occupied zone of a furnished room and the downstream distance from the inlet to the beginning of the furniture volume is shown. The maximum velocity in the furnished room, $u_{rm}$, is non-dimensionalized with the maximum velocity in the occupied zone of the empty room, $u_{rm,0}$. The downstream distance from the inlet to the beginning of the furniture, $L_{i-f}$, is non-dimensionalized with the distance from the inlet to the opposite end wall, L'. Results from the experiments and the simulations in all three lengths of the room are plotted in the figure. Furthermore the regression line from the simulations is drawn in the figure. The equation for the regression line is:

$$\frac{u_{rm}}{u_{rm,0}} = 0.20\frac{L_{i-f}}{L'} + 0.56 \qquad for\ 1.5 \le L/H \le 3.0 \tag{4}$$

where
- $u_{rm}$ : Maximum velocity in the occupied zone in the furnished room [m/s].
- $u_{rm,0}$ : Maximum velocity in the occupied zone in the empty room [m/s].
- $L_{i-f}$ : Downstream distance the jet travels from the inlet to the beginning of the furniture [m].
- $L'$ : Distance from the inlet to the opposite end wall [m].

Discussion of the maximum velocity is made in the previous section: Maximum Velocity in the Occupied Zone and the Total Length of the Furniture Volume.

Figure 8 shows that when the furniture volume is located only in the room half with the inlet (the three values to the right in figure 8 (the 3.75 m long room)) the maximum velocity in the furnished room is almost identical with the maximum velocity in the empty room. The regression line is only valid for $L_{i-f}/L' < 2.2$.

Figure 8 and equation (4) show that an increasing downstream distance from the inlet to the furniture volume increases the maximum velocity in the occupied zone.

## CONCLUSION

In this paper it is investigated how normal office furniture influences the air movements in a room with mixing ventilation. The influence on the jet under the ceiling is studied together with the maximum velocity in the occupied zone.

Isothermal, full-scale experiments and two-dimensional, isothermal CFD simulations form the basis for the investigations. In the experiments normal office furniture is placed symmetrically around the centre-line of the room and the furniture is only present in the half of the room opposite to the inlet. The simulations of the experiments are made in a simular room but instead of inserting the furniture individually a volume resistance generating a pressure drop is used. Further simulations are made with other dimensions and locations of the volume resistance. Finally, some of the simulations are repeated in a shorter room and a longer room.

The jet under the ceiling is examined to see if the flow element theory (throw) developed in empty rooms also is valid in normally furnished rooms. To investigate the disturbance of the jet, the velocity decay at the ceiling is examined. It is found that the jet is not disturbed by the furniture in the room.

The maximum velocity in the occupied zone of a furnished room is reduced compared to an empty room. The maximum velocities found in the experiments are lower than the ones found in the simulations with $f$=0.5. The reason is that in the experiments the air is forced to go around the physical furniture whereas in the simulations the volume resistance makes an uniform disturbance to the flow and since $f$ is determined on basis of the flow outside the furniture area this difference occurs.

The maximum velocity in the occupied zone is studied in connection with the total length of the furniture (volume) and in connection with the downstream distance from the inlet to the beginning of the furniture (volume). In the investigations results from the experiments and the simulations in the three lengths of the room are used. It is found that the maximum velocity in the occupied zone decreases when the furniture volume increases. Furthermore, it is found that the length of the room has no influence on this reduction. The location of the furniture is also important because the maximum velocity in the occupied zone increases with increasing downstream distance from the inlet to the beginning of the furniture volume.

It can, on basis of the investigations made in this paper, be concluded that normal office furniture does not influence the air movements in the upper part of the room but it reduces the maximum velocity in the occupied zone compared to an empty room. This reduction is dependent of the length and location of the furniture.

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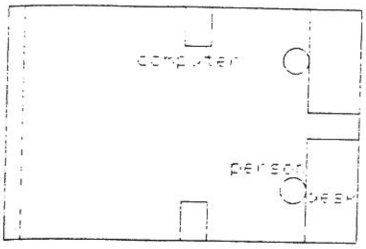
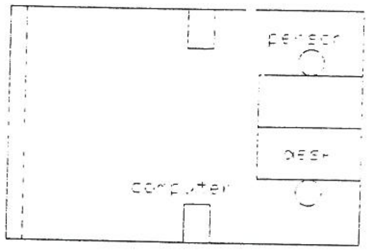
## Figures

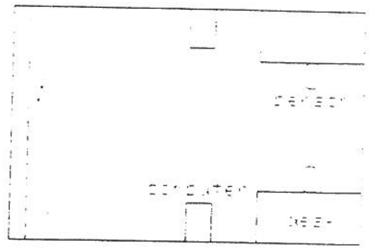
**Figure 1** Example of an empty and a funished office. The latter indicates a large disturbance to the flow field.




*Experimental set-up 1*




*Experimental set-up 2*




*Experimental set-up 3*

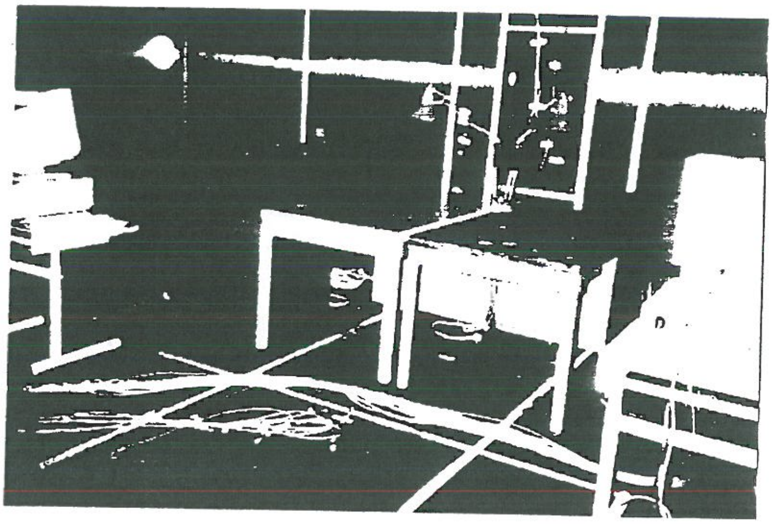
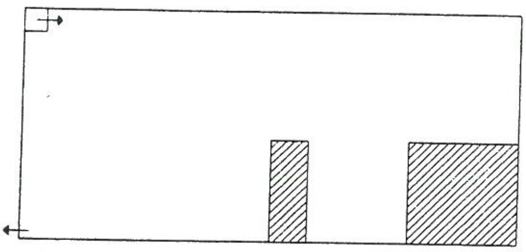
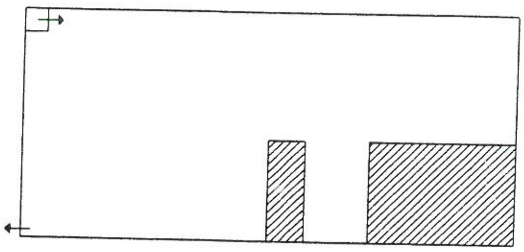


*Photo of experimental set-up 2*

**Figure 2** The experimental set-ups with normal office furniture.

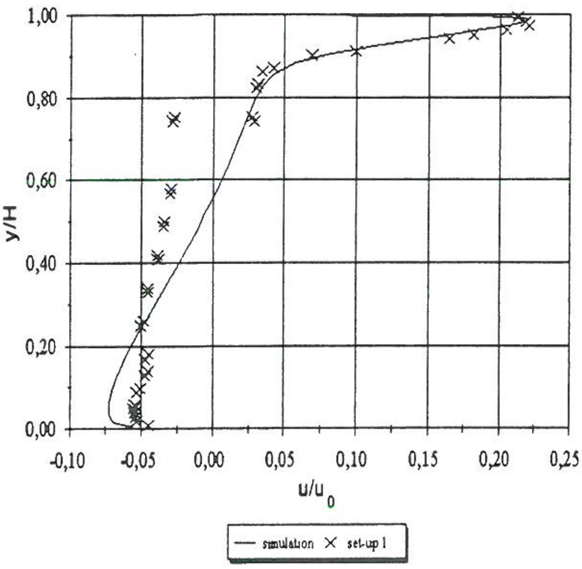


*Simulation of set-up 1*

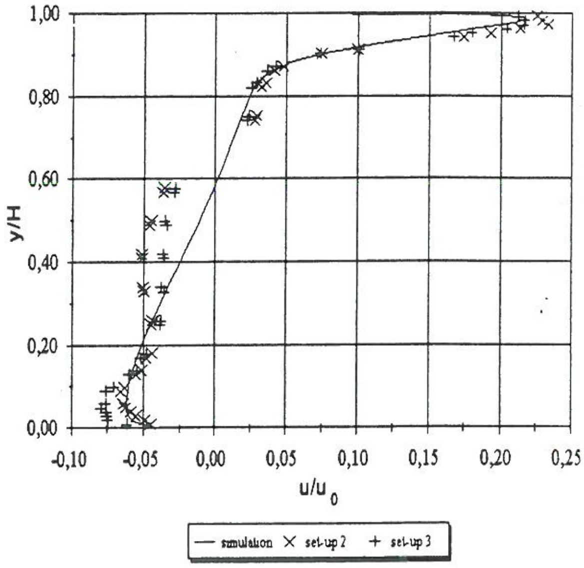


*Simulation of set-up 2 and 3*

**Figure 3** The location of the air inlet and the volume resistances used in the simulations of the experimental set-ups.

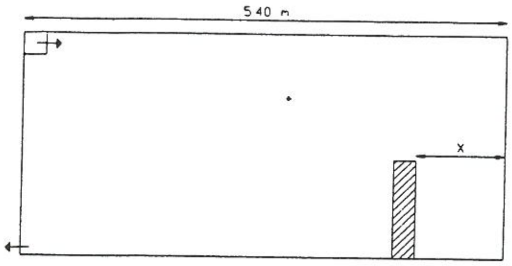



*Velocity profiles in set-up 1*

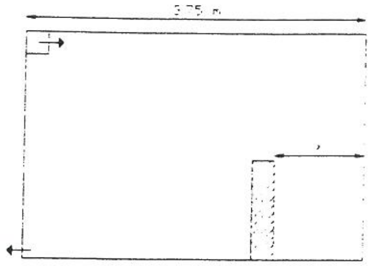



*Velocity profiles in set-up 2 and 3*

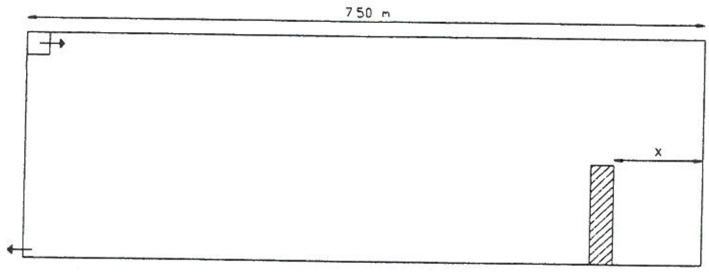
**Figure 4** *Comparison of the non-dimensional velocity profiles 2.0 m from the inlet found in the experiments and in the simulations with f=0.5.*




*Volume in the 5.40 m room*

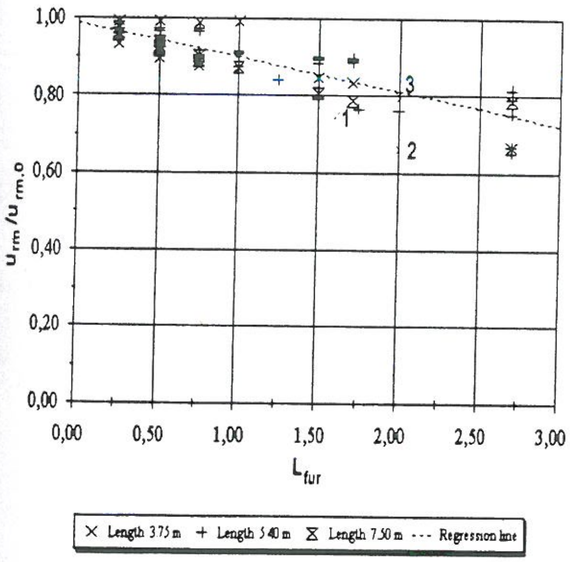


*Volume in the 3.75 m room*



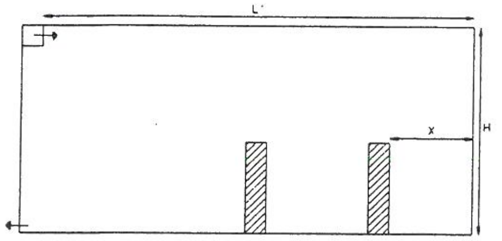

*Volume in the 7.50 m room*

**Figure 5** *Examples with a volume resistance (L×H) 0.25×1.1 m in three different rooms.*



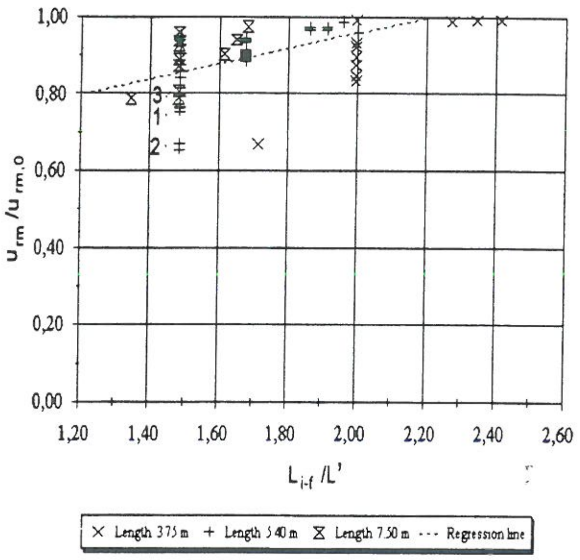

×1-×3: Experiment 1-3

**Figure 6** *The non-dimensional maximum velocity in the occupied zone as a function of the total length of the furniture volume.*




$L_{i\text{-}f}=L'+H+X.$

**Figure 7** *Determination of downstream distance from inlet to beginning of furniture, $L_{i\text{-}f}$*




×1-×3: Experiment 1-3

**Figure 8** *The non-dimensional maximum velocity in the occupied zone as a function of the non-dimensional downstream distance from the inlet to the beginning of the furniture.*